Climate Intervention Strategies

What have we learned from a decade of coordinated GeoMIP and stand-alone-SRM geoengineering simulations?

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MacMartin, Douglas G., Ben Kravitz, Jane CS Long, and Philip J. Rasch. "Geoengineering with stratospheric aerosols: What do we not know after a decade of research?." *Earth's Future* 4, no. 11 (2016): 543-548.

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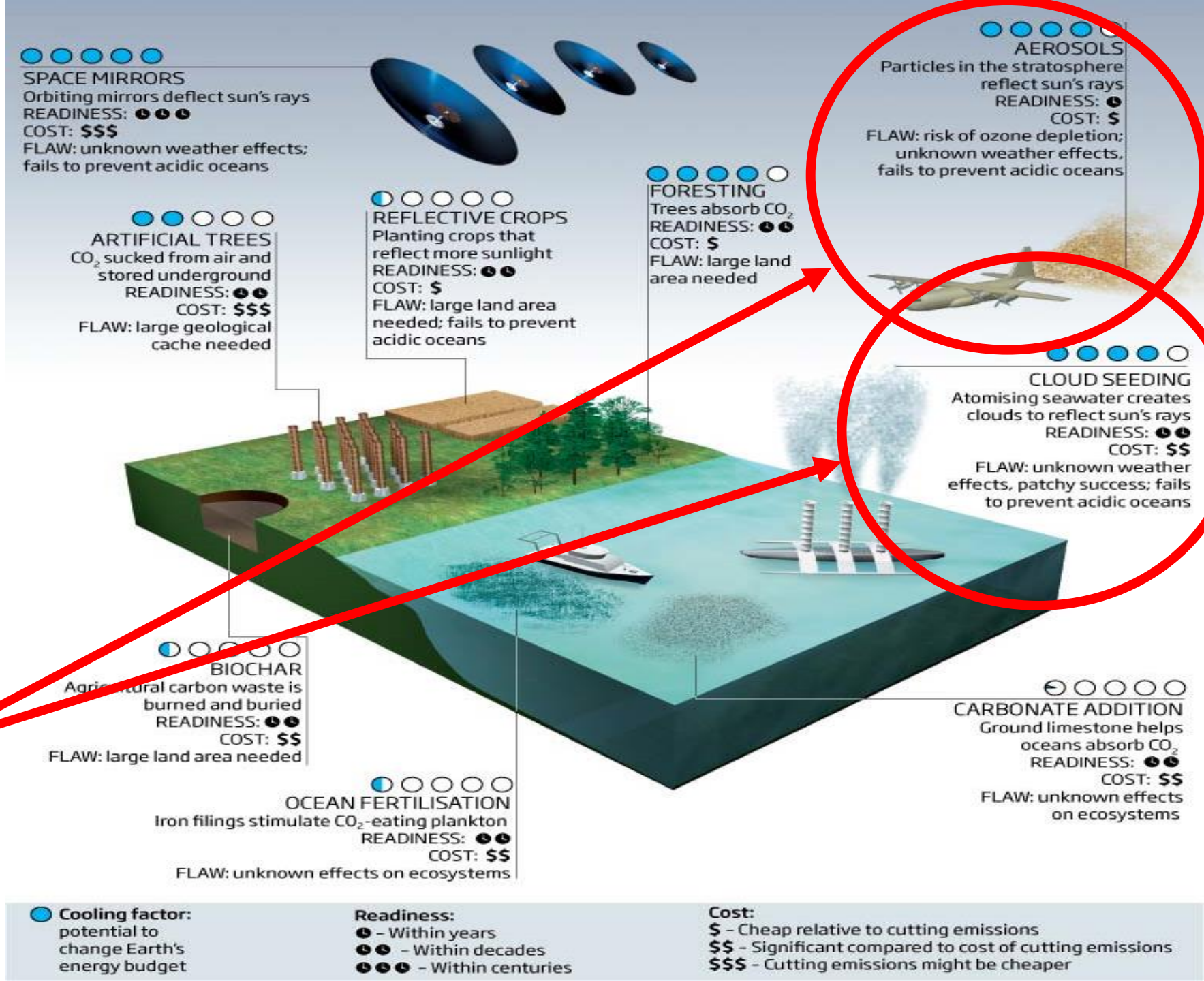
Schematic of geoengineering

1) **Effectiveness**
2) **Readiness**
3) **Cost**
4) **Safety**



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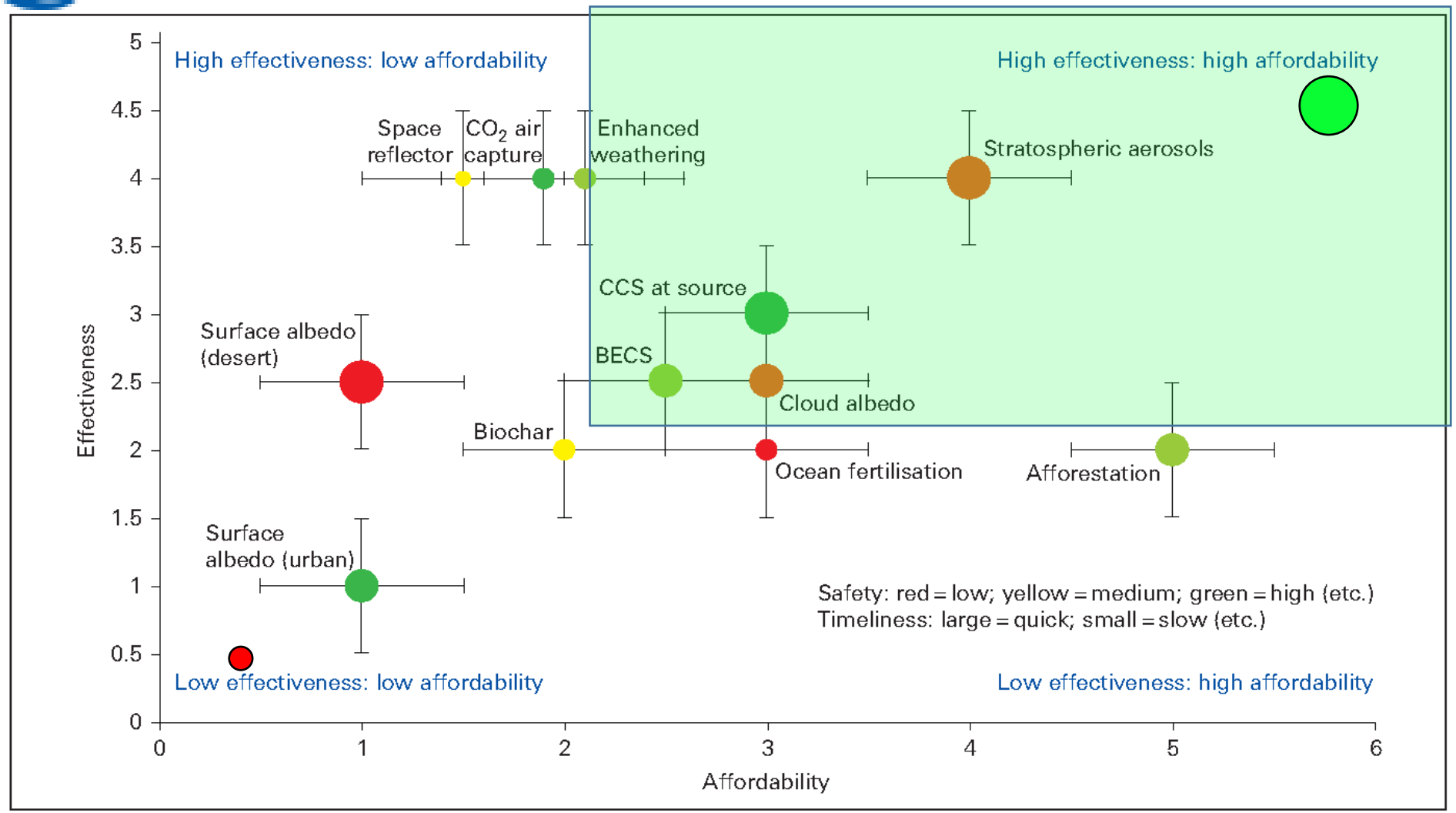
4-D plot of geoengineering options: Royal Society Report, 2009.



The Geoengineering Model Intrcomparison Project: GeoMIP: http://climate.envsci.rutgers.edu/GeoMIP/

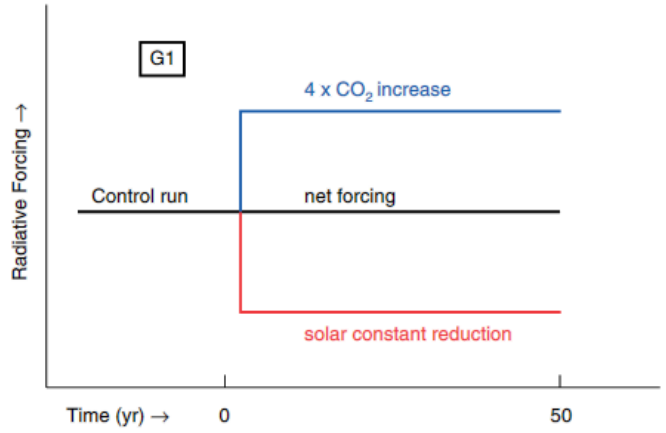
The largest set of coordinated modelling studies examining SRM is GeoMIP.

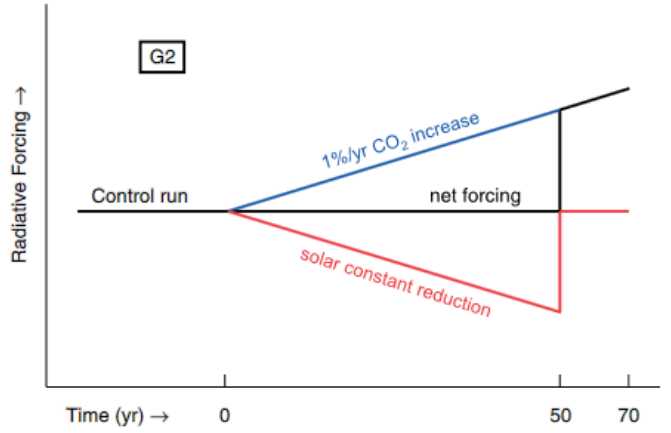
This has evolved from simple-minded experiments where the sun is simply turned down to complex stratospheric sulphur scheme with bin/sectional/modal models.

The most recent GeoMIP6 experiments include more realistic specific policy-relevant scenarios. e.g. turning RCP8.5 temperature (high end warming scenarios) into RCP4.5 (medium warming scenarios). They are the same models that are used for global warming projections.

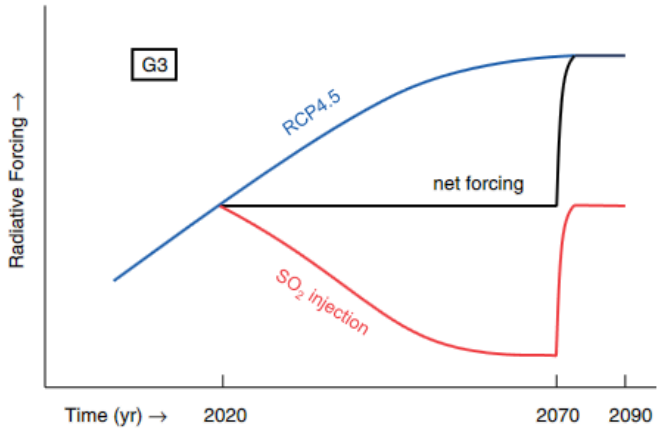
GeoMIP: was formed because it is difficult to assess inter-model differences when the forcing is not consistent between models:-

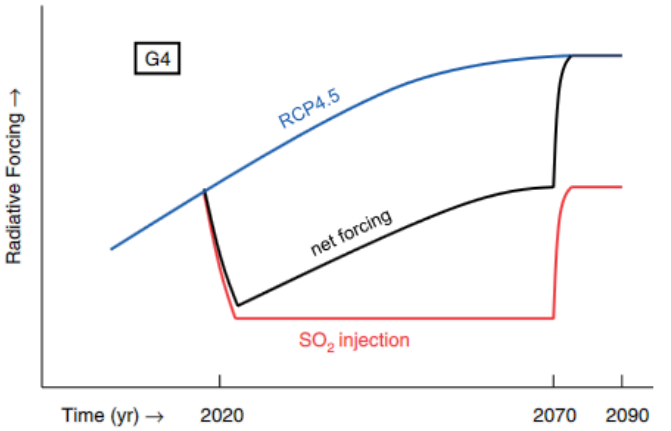
- **86 publications** since 2011: http://climate.envsci.rutgers.edu/GeoMIP/publications.html
- First tranche of experiments (G1-G4):





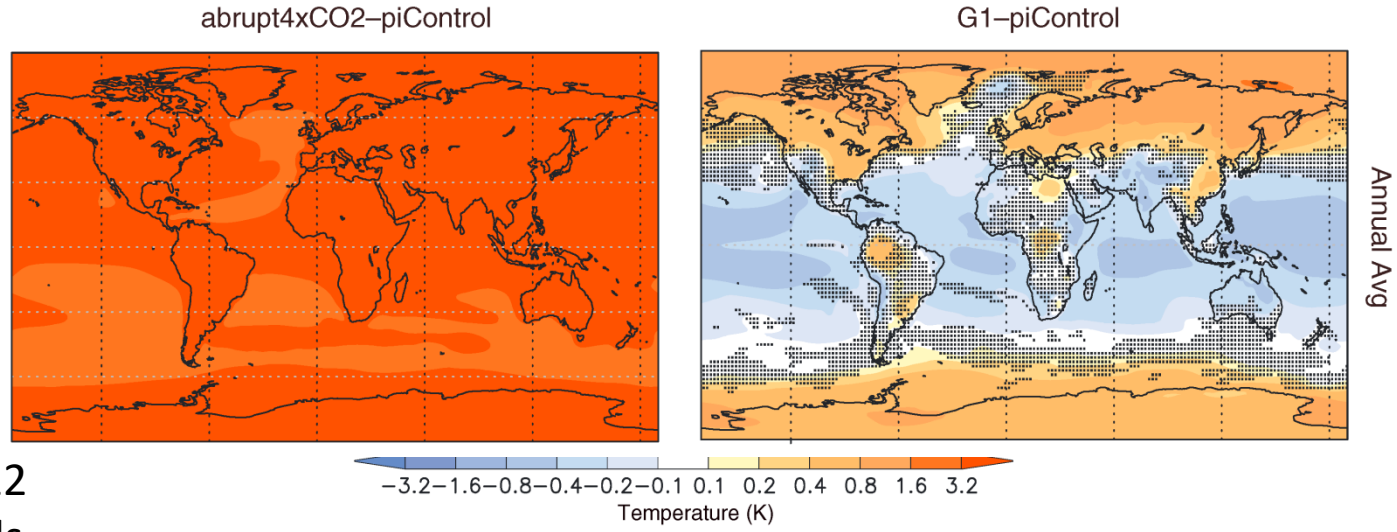
Solar constant reduction
= easy
= lots of models



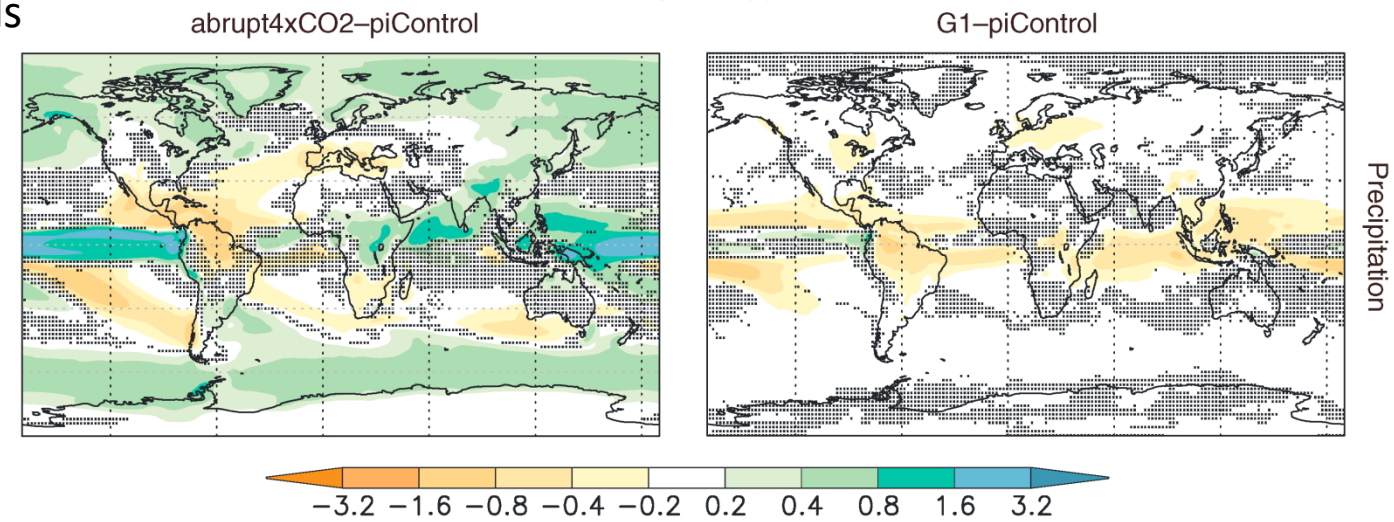


SO2 injection (or prescription from other models)
= harder
= fewer models

GeoMIP finding #1 (G1 expiment): continued warming in polar regions and the overcooling of the tropics



Ensemble of 12 climate models



Some residual temperature impacts…. But relatively small in magnitude

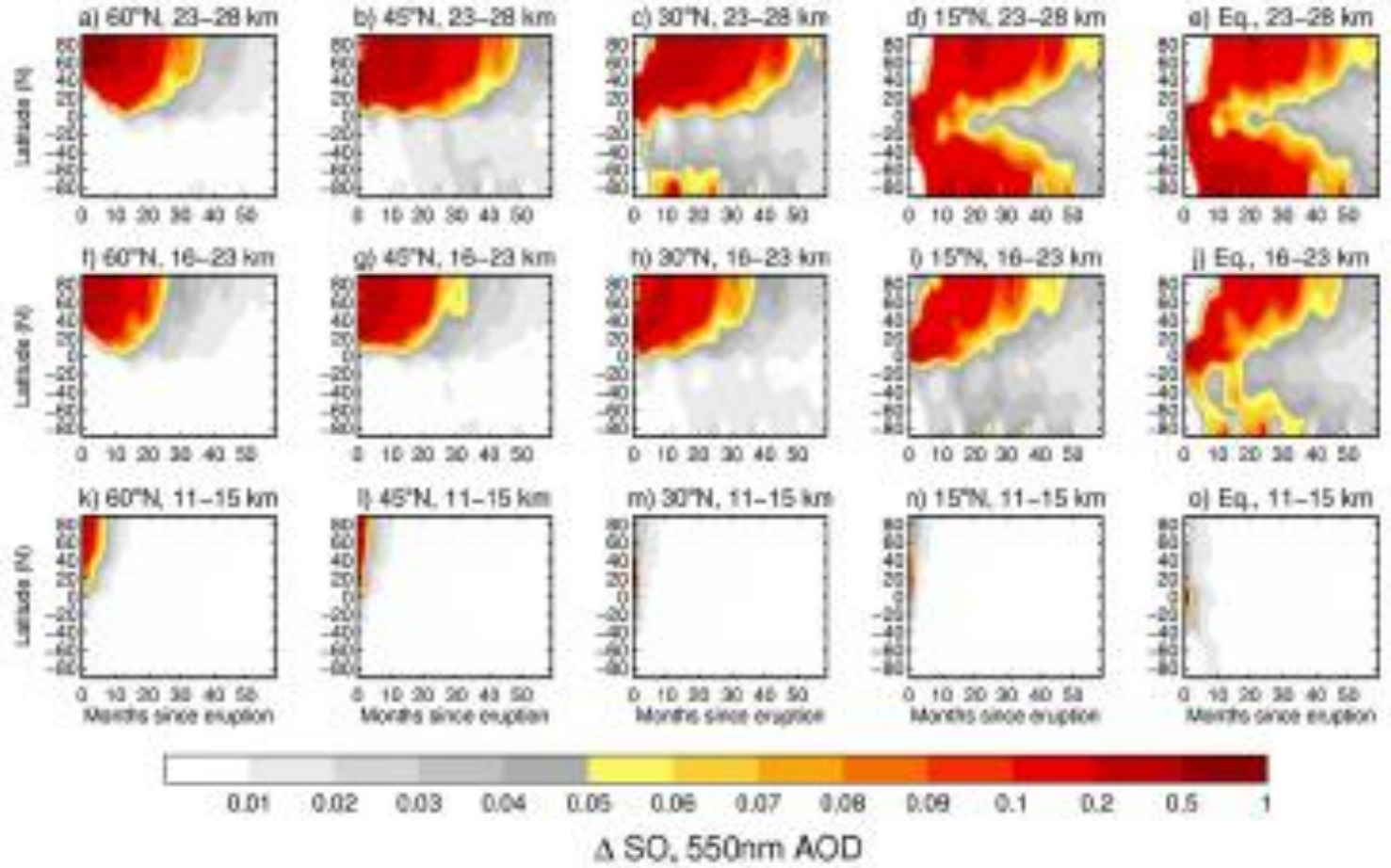
Some residual precipitation impacts…. But less than non-geoengineered case

Kravitz et al., JGR, 2012

GeoMIP: Geoengineering Model Intercomparison Project: G1: Balancing the radiative forcing from 4xCO2 with solar dimming

Dependence of the resulting distribution of aerosol on the altitude & latitude of the injection

Injection at higher altitudes ->



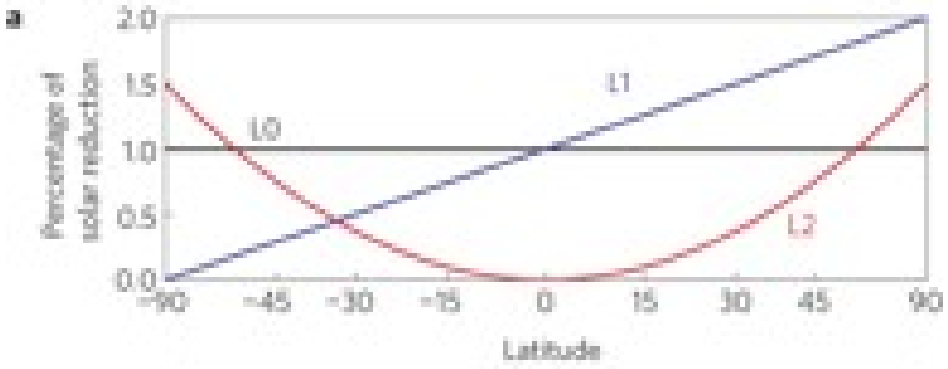
Injection closer to the equator->

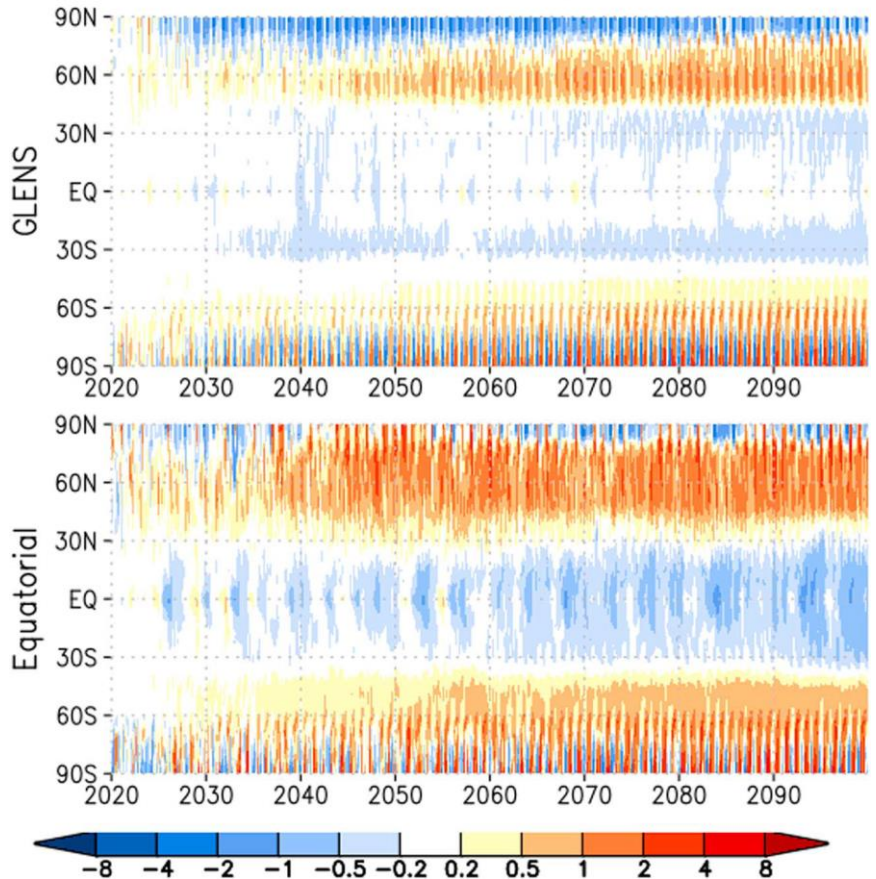
Need to inject at high altitudes near the Equator to maximise the lifetime of the aerosol.

Jones et al., Impacts of hemispheric solar geoengineering on tropical cyclone frequency, *Nature Communications, 2017*.

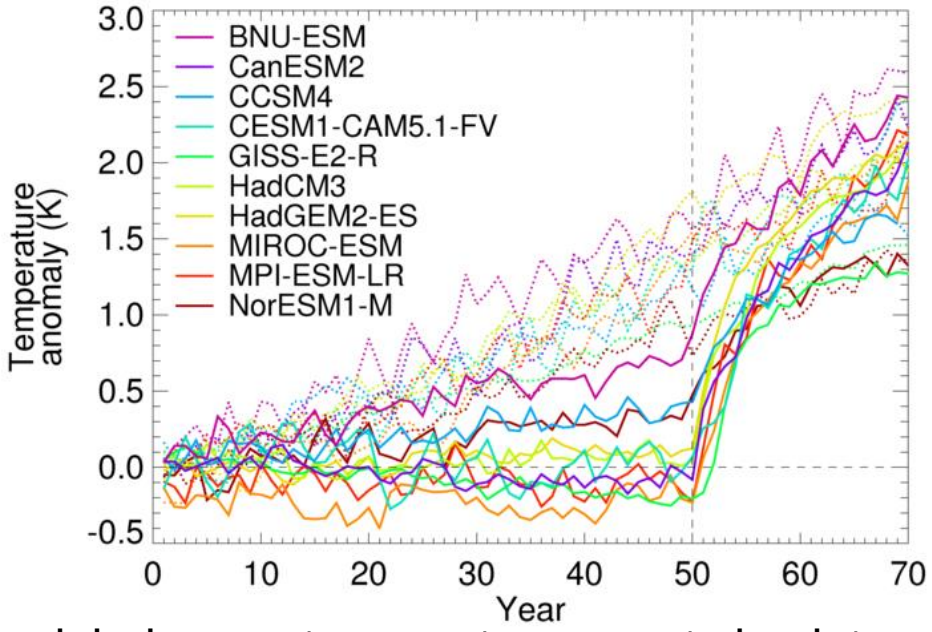
Research that follows:

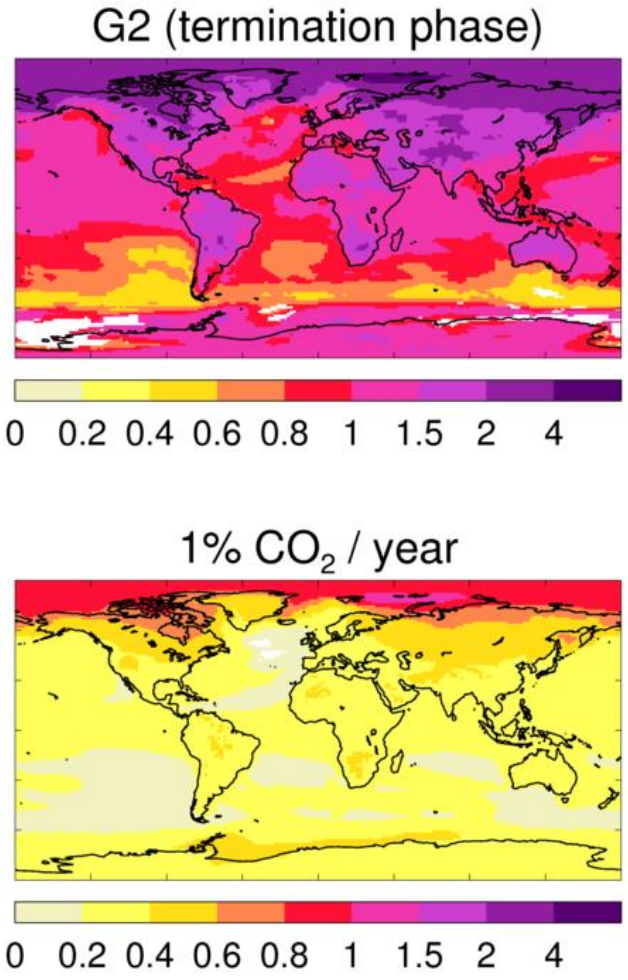
- MacMartin, et al., Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. *Nature Climate Change*, *3*(4), 365-368.
- Kravitz, B., MacMartin, D. G., Tilmes, S., Richter, J. H., Mills, M. J., Cheng, W., et al. (2019). Comparing surface and stratospheric impacts of geoengineering with different SO2 injection strategies. Journal of Geophysical Research: Atmospheres, 124, 7900–7918. https://doi.org/10.1029/2019JD030329
- The warming of the poles is much less than in global warming scenarios. You CAN avoid the worst of the overwarming by tailoring the injection strategy.





GeoMIP finding #2 (G1 experiment): the termination effect is potentially a serious issue





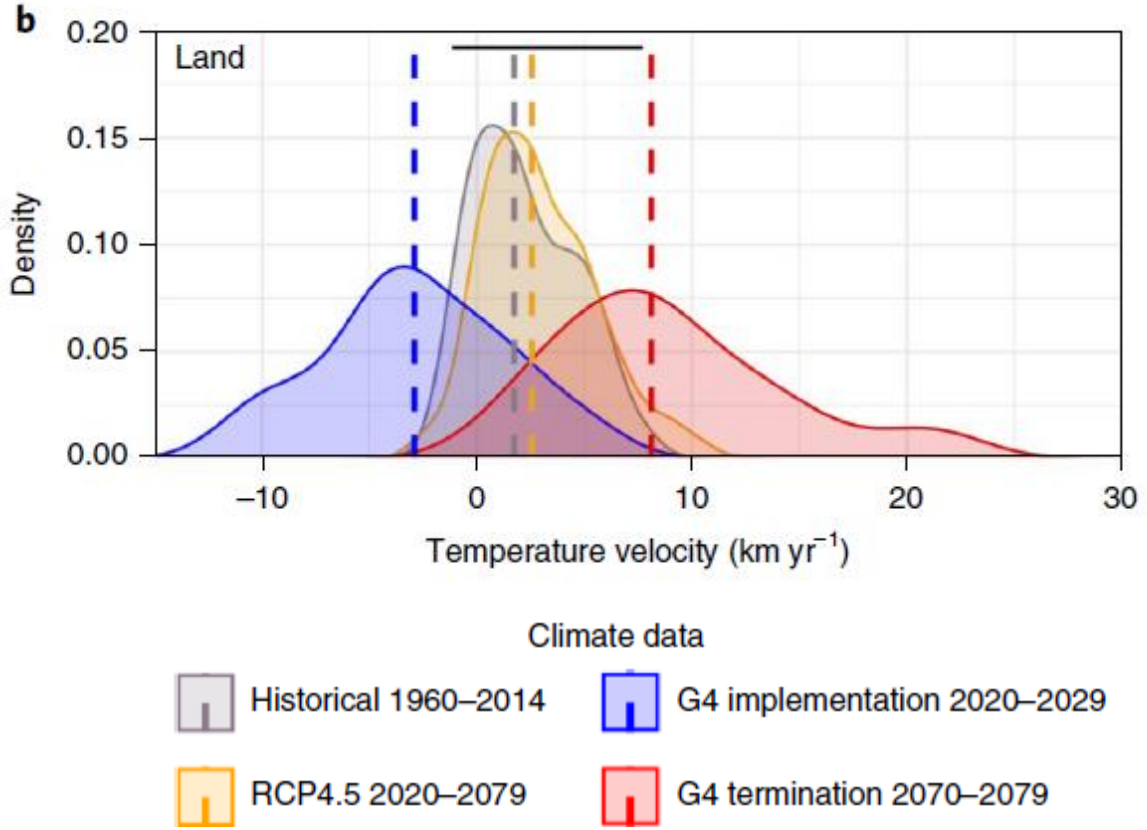
The global mean temperature reverts back to pre-geoengineered state within 5-10years on cessation. Regional warming can be many times the global mean.

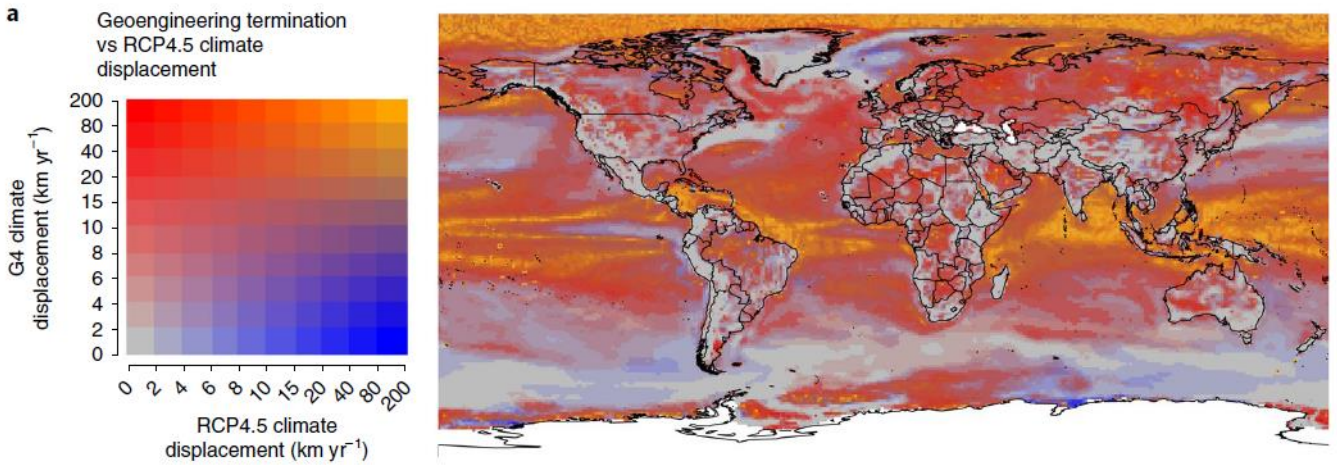
The rate of temperature change after termination is many times more than under business as usual scenarios: potential impacts on ecosystems and adaptability

Jones et al., 2013

Research that follows:

- Trisos, Christopher H., Giuseppe Amatulli, Jessica Gurevitch, Alan Robock, Lili Xia, and Brian Zambri. "Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination." *Nature Ecology & Evolution* 2, no. 3 (2018): 475-482.





Research that follows:

- Not a single scientist (that I know of) is suggesting that we can just keep on emitting fossil-fuels and balance the warming with an ever increasing veil of sulphate aerosol. Scientists are widely debating “peak-shaving”:-

Jones, A. C., et al. Earths Future, 2018

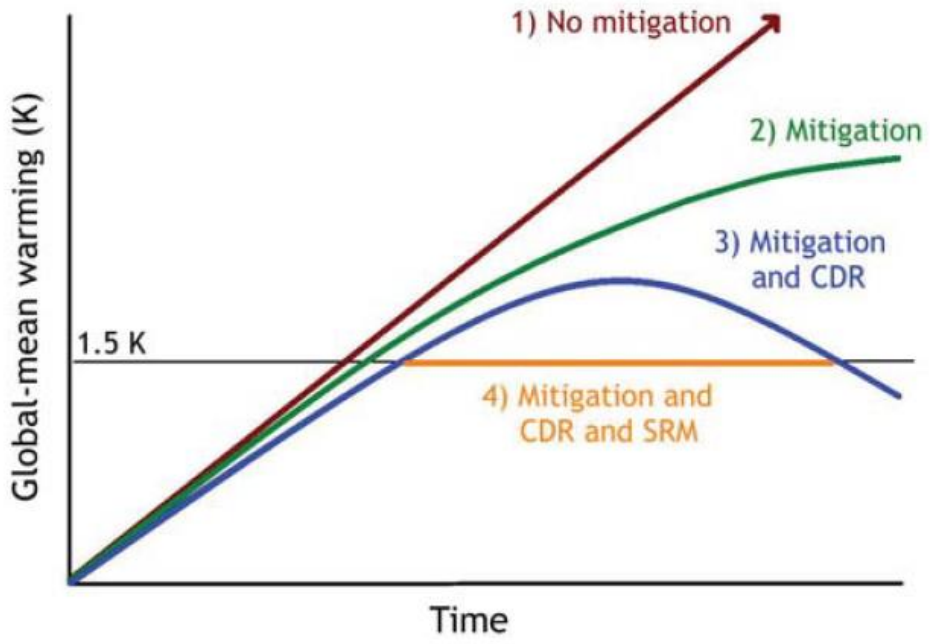
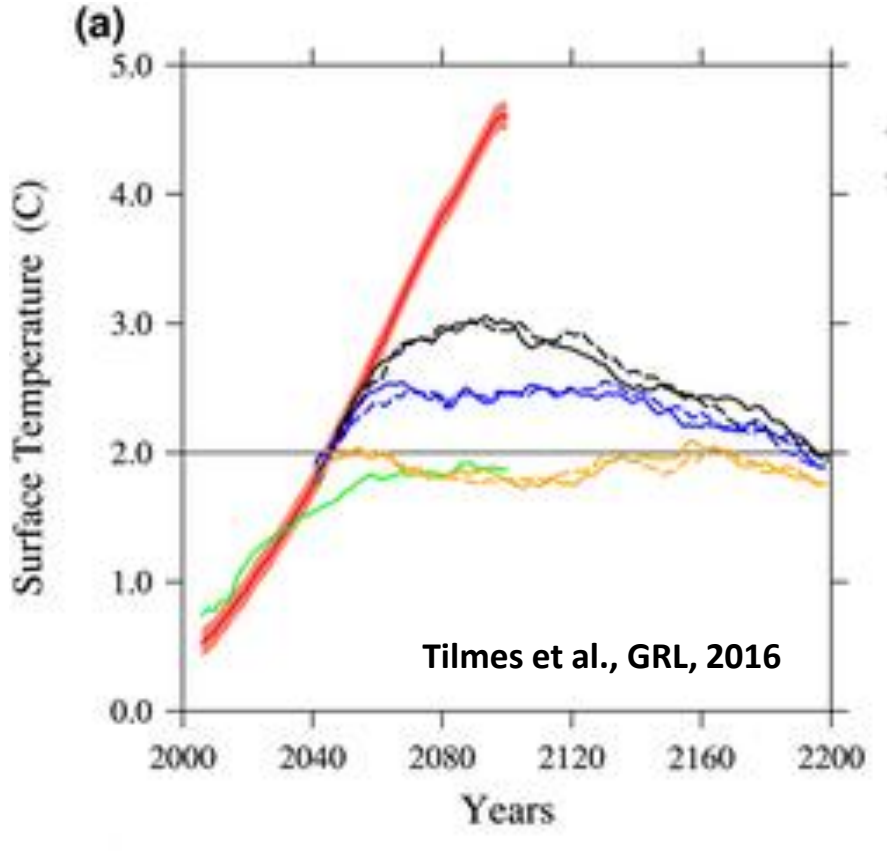


Figure 1. Schematic of 21st century global warming trends under various scenarios (credit to David MacKay). Note: the similarity between this schematic and Figure 2 of Tilmes et al. (2016).



Tilmes et al., GRL, 2016

GeoMIP finding #3 (G1 experiment): regional extremes are ameliorated

Table 3. Efficacy[a] of *G1* for Neutralizing Annual Extremes in *abrupt4* × CO_2

Variable	Global	Land	Ocean
TNn	0.87	0.86	0.88
TXx	0.89	0.88	0.91
Rx5day	0.71	0.77	0.70
CSDI	−1.34	0.0743	−1.55
WSDI	0.96	0.92	0.98
CDD	0.71	0.77	0.67

[a]The efficacy *e*, defined in equation (2), is the fraction of RMS change in *abrupt4* × CO_2 relative to *piControl* that is offset by the solar irradiance reduction in *G1*. The value of *e* ranges from negative values (indicating differences are larger in *G1* than in *abrupt4* × CO_2) through 0 (low efficacy) to 1 (high efficacy). RMS values for each experiment are provided in Table 2 of the supporting information.

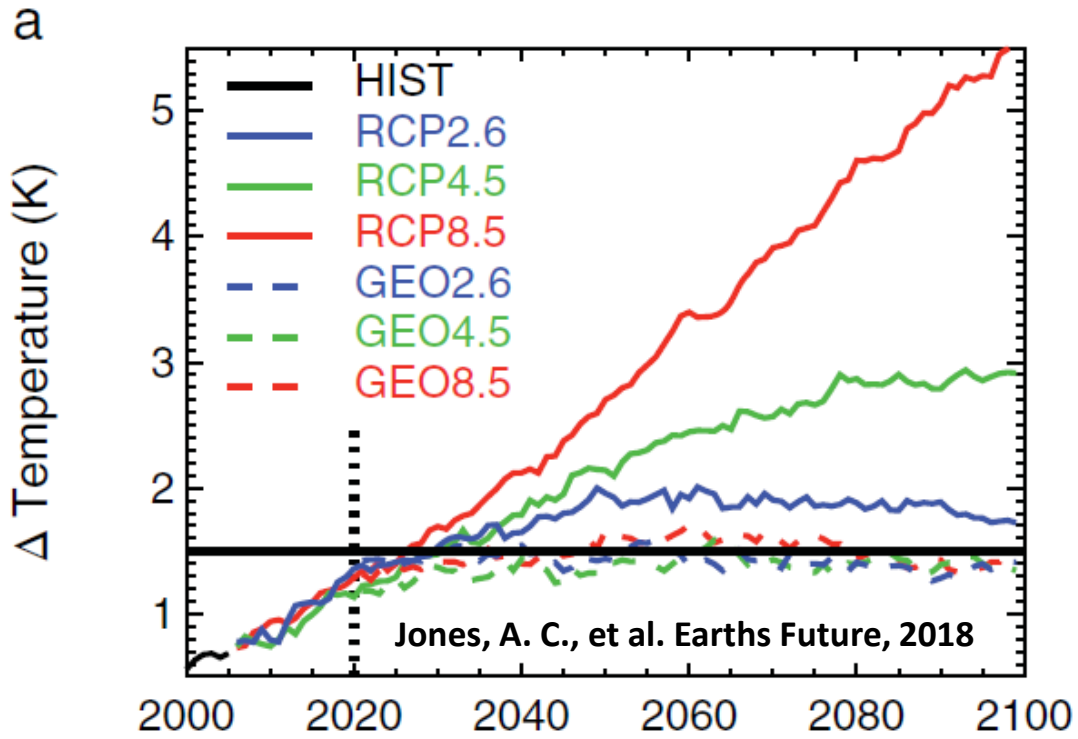
Coldest daily Tmin
Warmest daily Tmax
5 day consecutive rainfall
Cold spell duration
Warm spell duration
Consecutive dry days

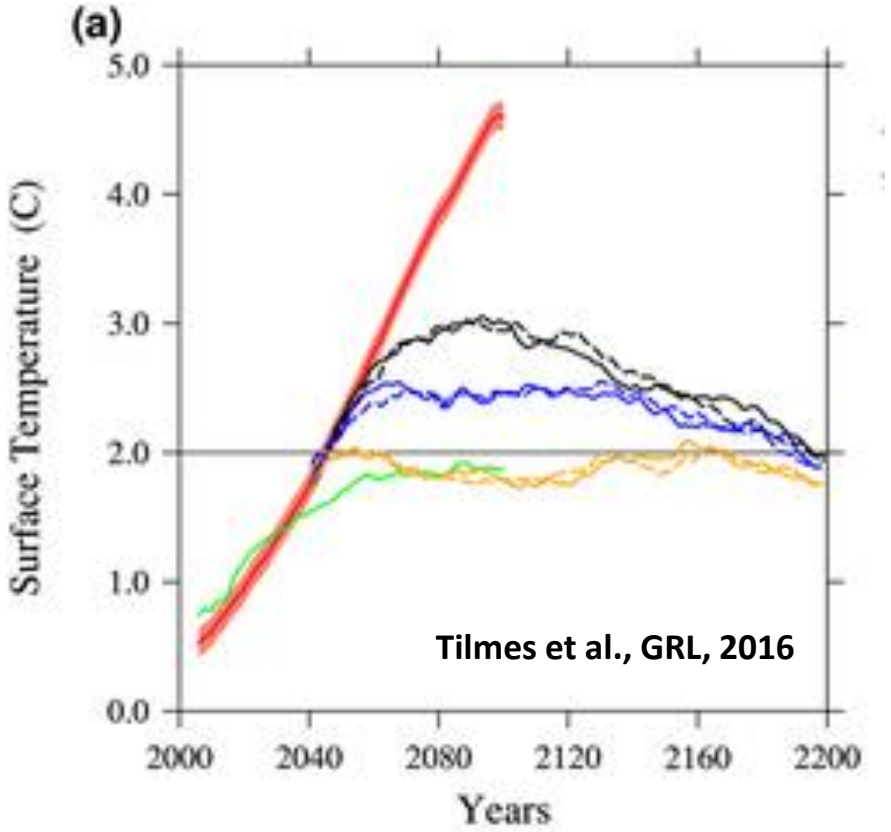
$$e(X) \equiv 1 - \frac{RMS_{G1-Ctl}(X)}{RMS_{4\times CO2-Ctl}(X)} = 1 - r(X),$$

Curry, C. L., et al. 2013. A multimodel examination of climate extremes in an idealized geoengineering experiment. *Journal of Geophysical Research – Atmospheres*, *119*, 3900–3923. https://doi.org/10.1002/2013JD020648

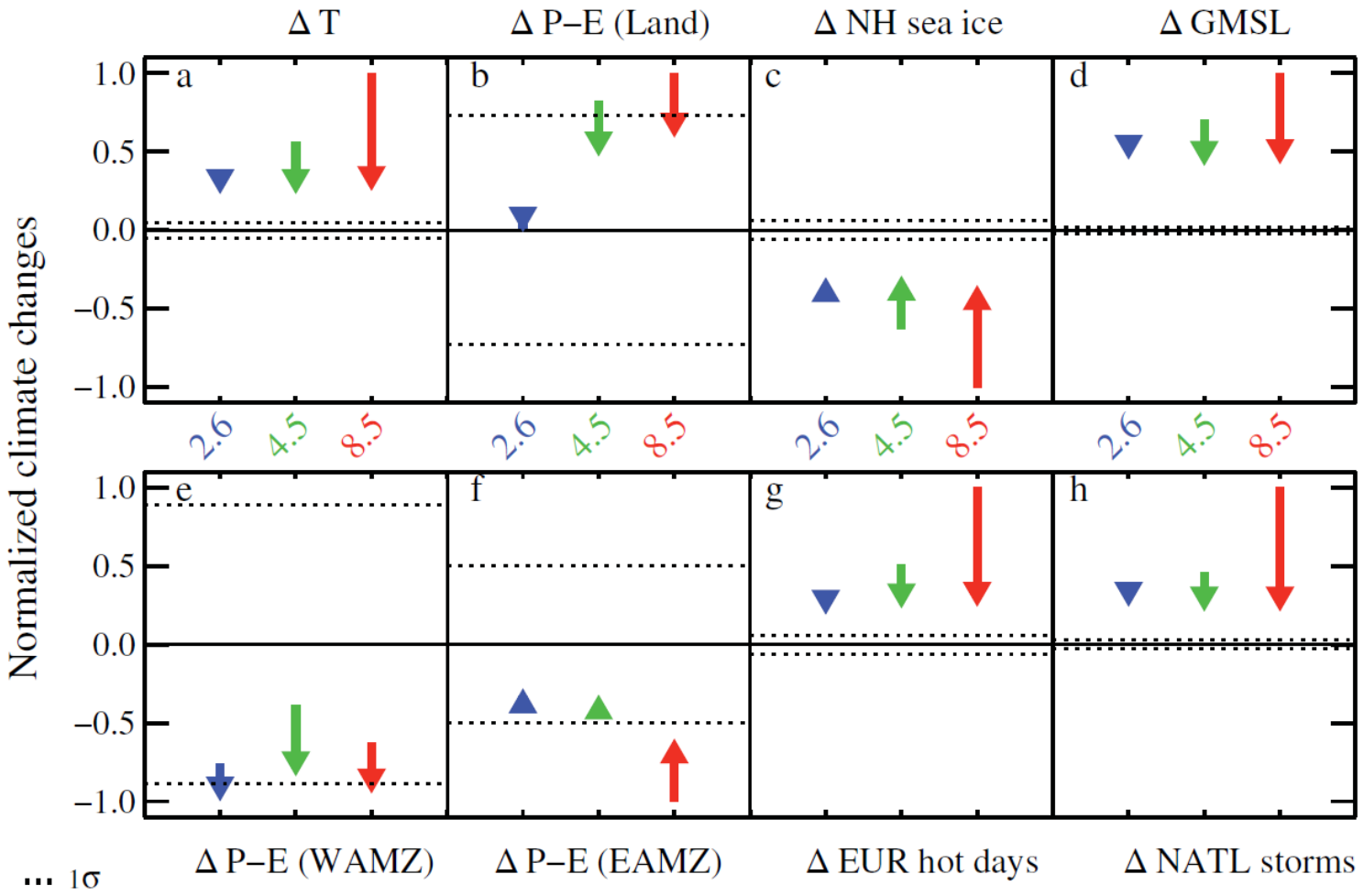
Research that follows:

- Much more realistic simulations that are policy-relevant
- Using realistic scenarios (not x4 CO2 balancing) to curb temperature increases at 1.5C (Jones et al., 2018) or 2C (Tilmes et al., 2016) :-





Research that follows:

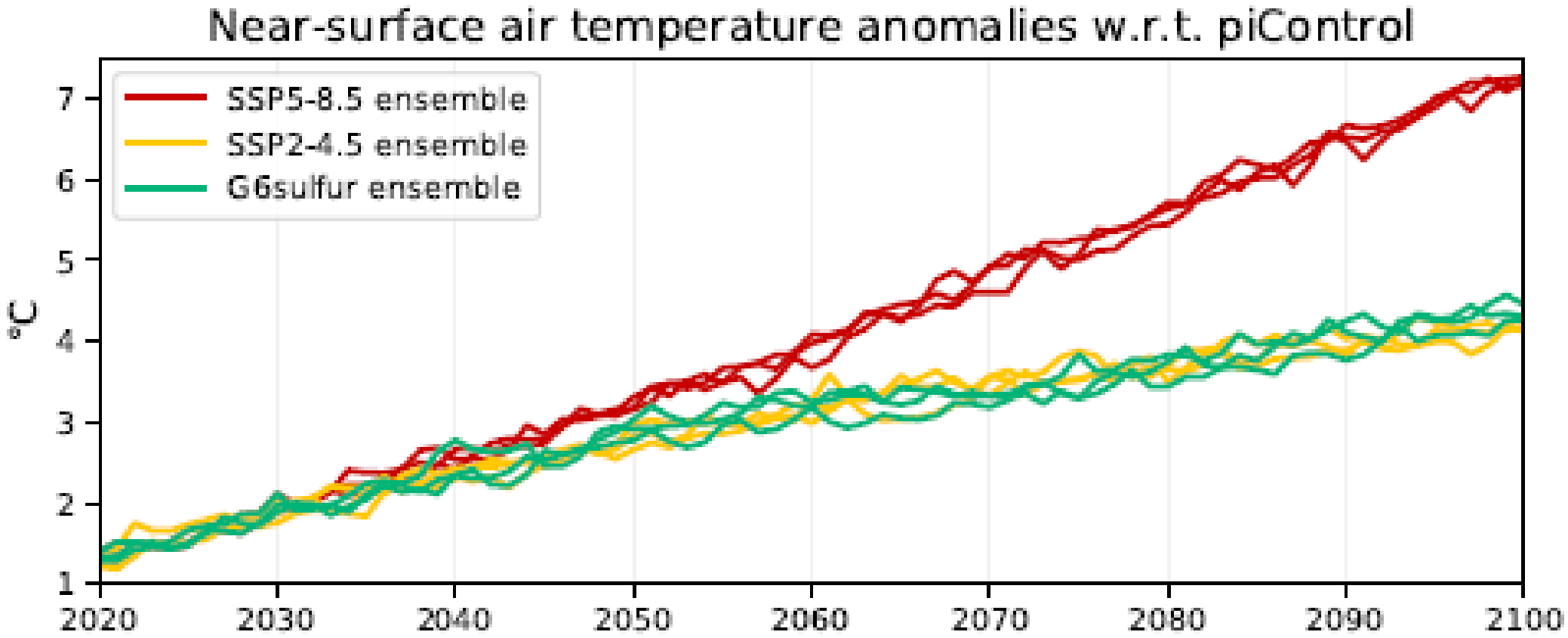


A whole basket of extremes are ameliorated if you reduce the temperature change:

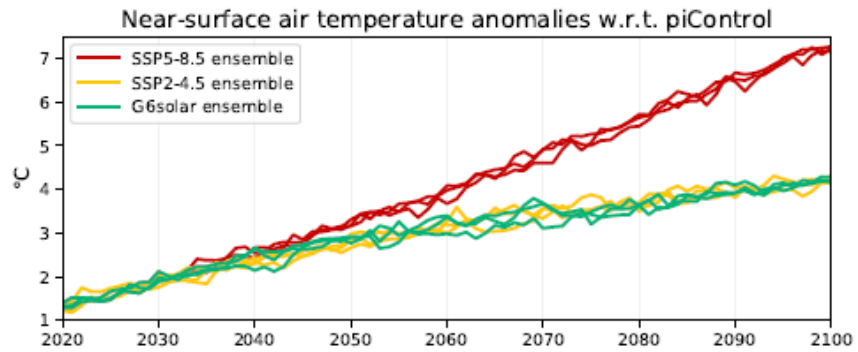
Jones, A. C., et al. (2018). Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering, *Earth's Future*, *6*, 230–251, https://doi.org/10.1002/2017EF000720

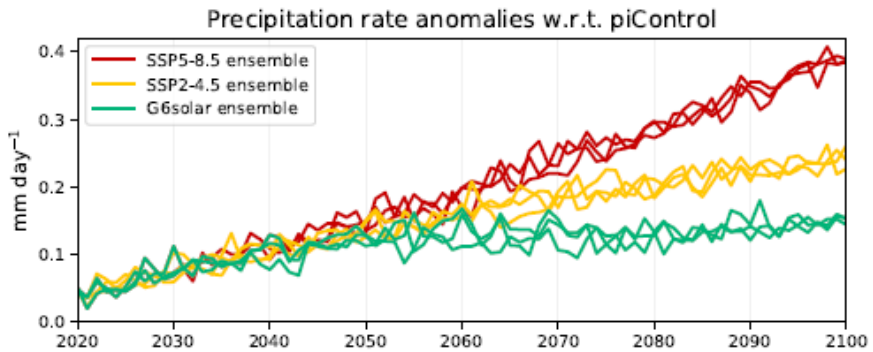
GeoMIP finding #4: realistic scenarios are needed

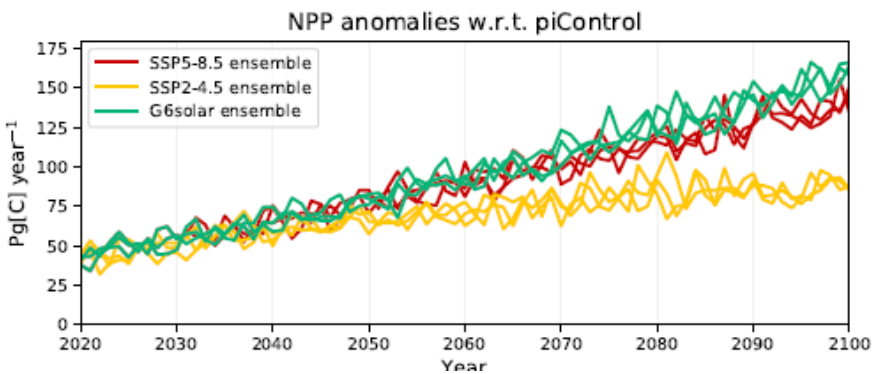
GeoMIP6: Reducing RCP8.5 to RCP4.5 temperatures



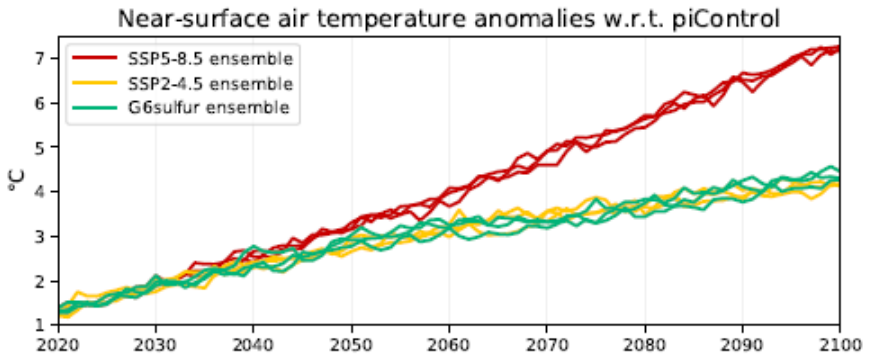
G6 solar

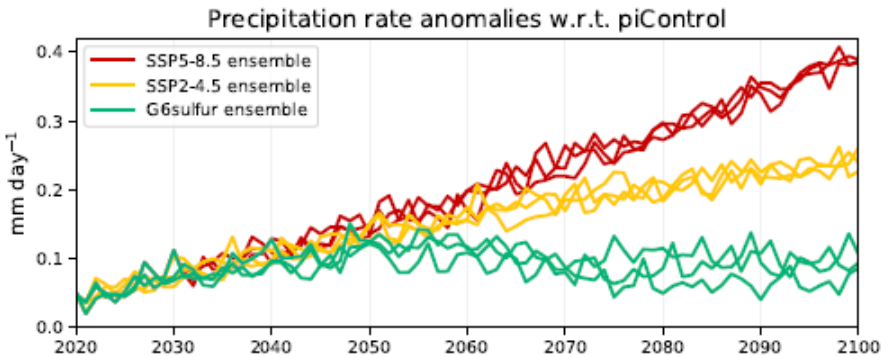


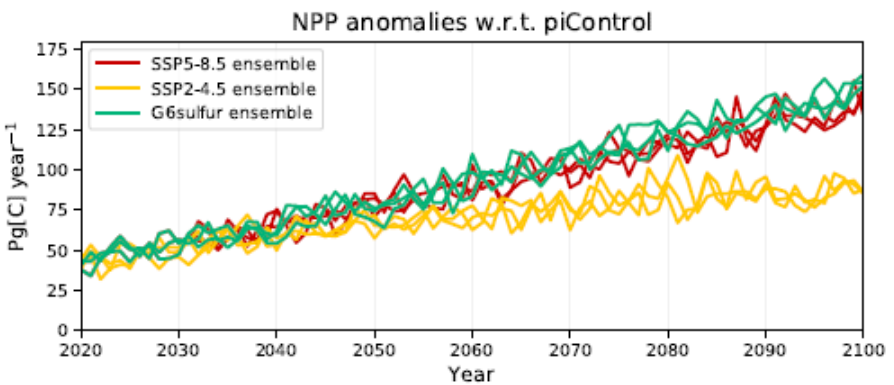




G6 sulphur



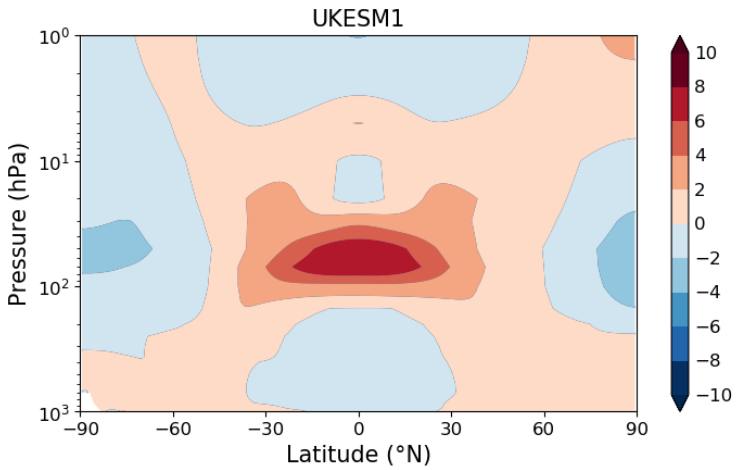


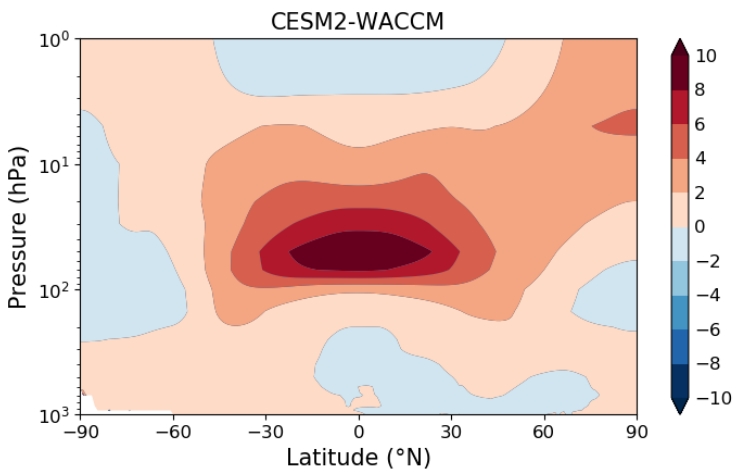


Why G6solar and G6sulphur?

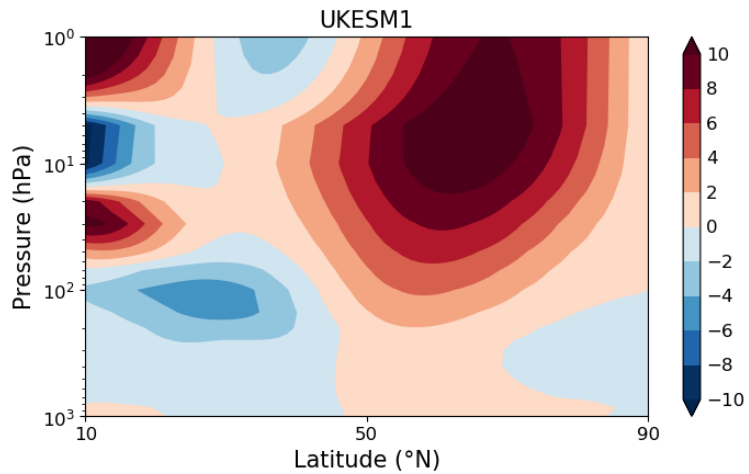
- Lots of models have performed G1 experiments (turning down the sun)
- Obviously these are simplistic.
- Are they too simplistic?

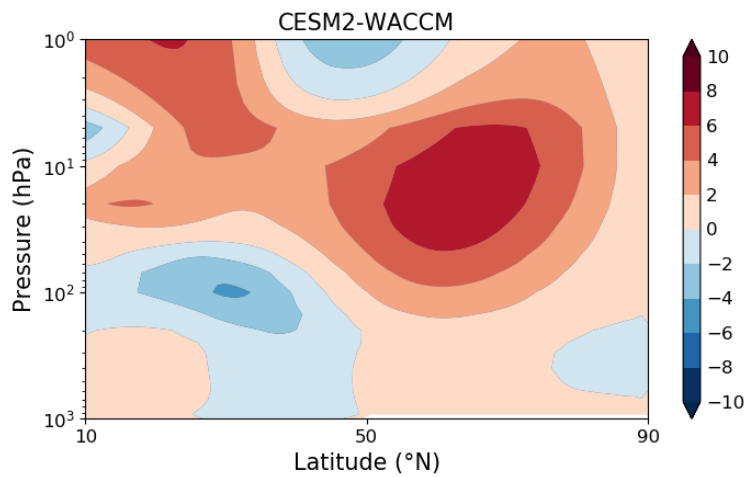
Difference in annual-mean temperature, 2080-2100 mean (K)
G6sulfur minus G6solar (ensemble means)



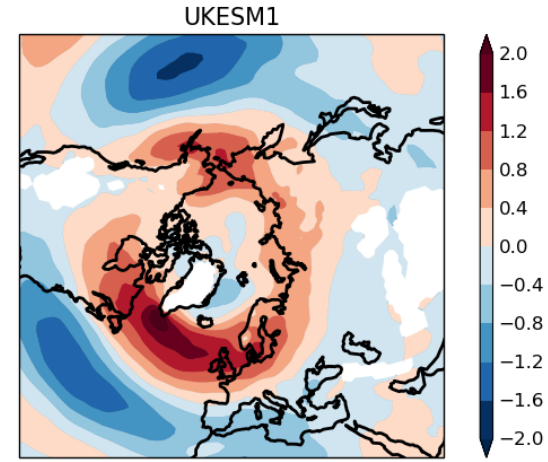


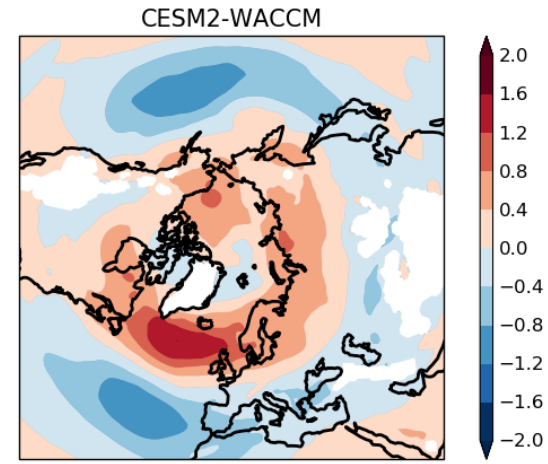
Difference in Oct-Mar zonal-mean wind 2080-2100 mean (m s^{-1})
G6sulfur minus G6solar (ensemble means)





Difference in Oct-Mar 850 hPa zonal wind, 2080-2100 mean (m s^{-1})
G6sulfur minus G6solar (ensemble means)

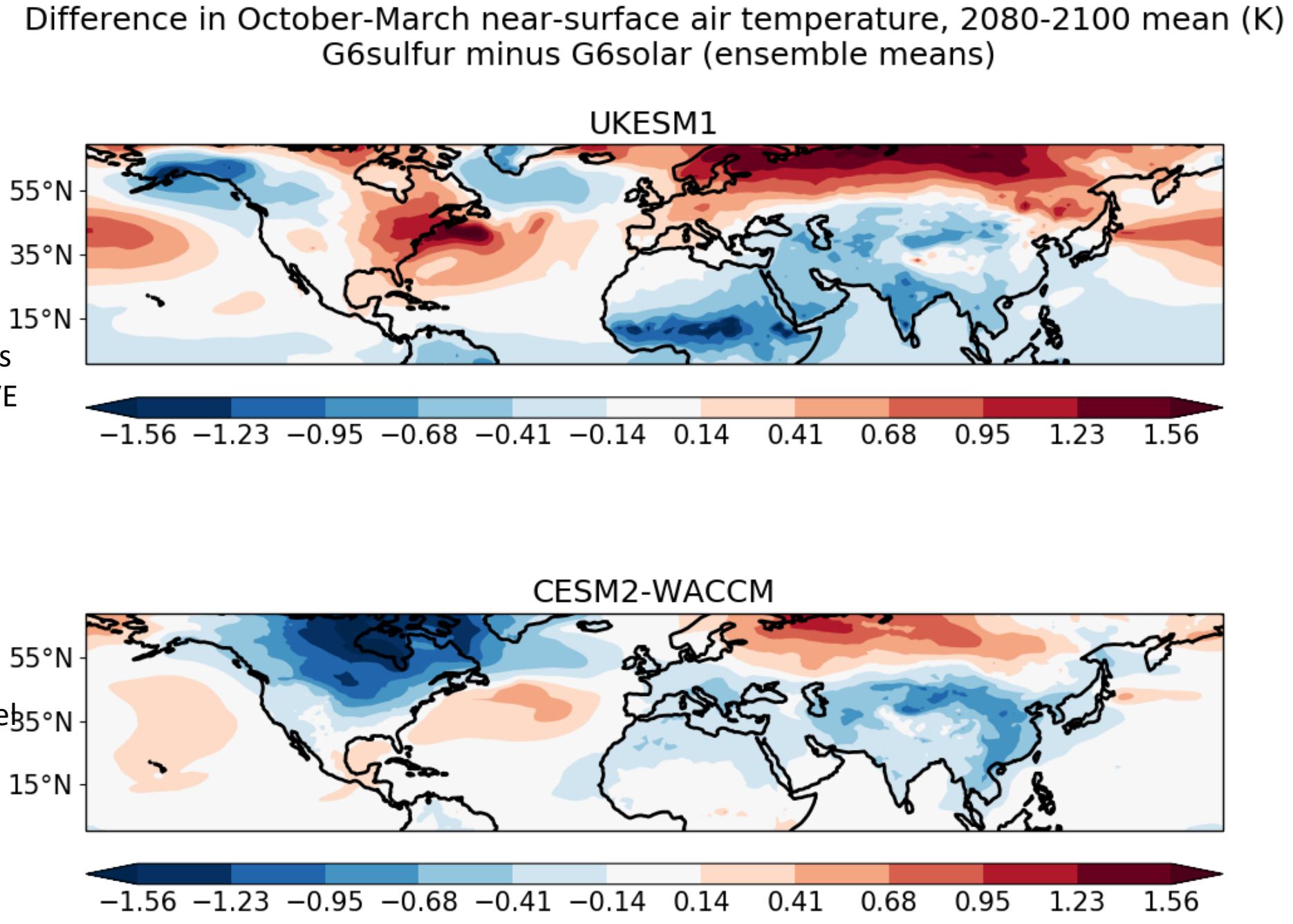




Impact of stratospheric SO_2 injection on N. Hem. *cold-season (Oct-Mar) mean* surface temperature (*cf*. Shindell *et al*. [2004]'s Fig. 2)

If we want to be able to model SRM at regional scales to examine impacts, we HAVE to include aerosols and stratospheric chemistry at reasonable complexity

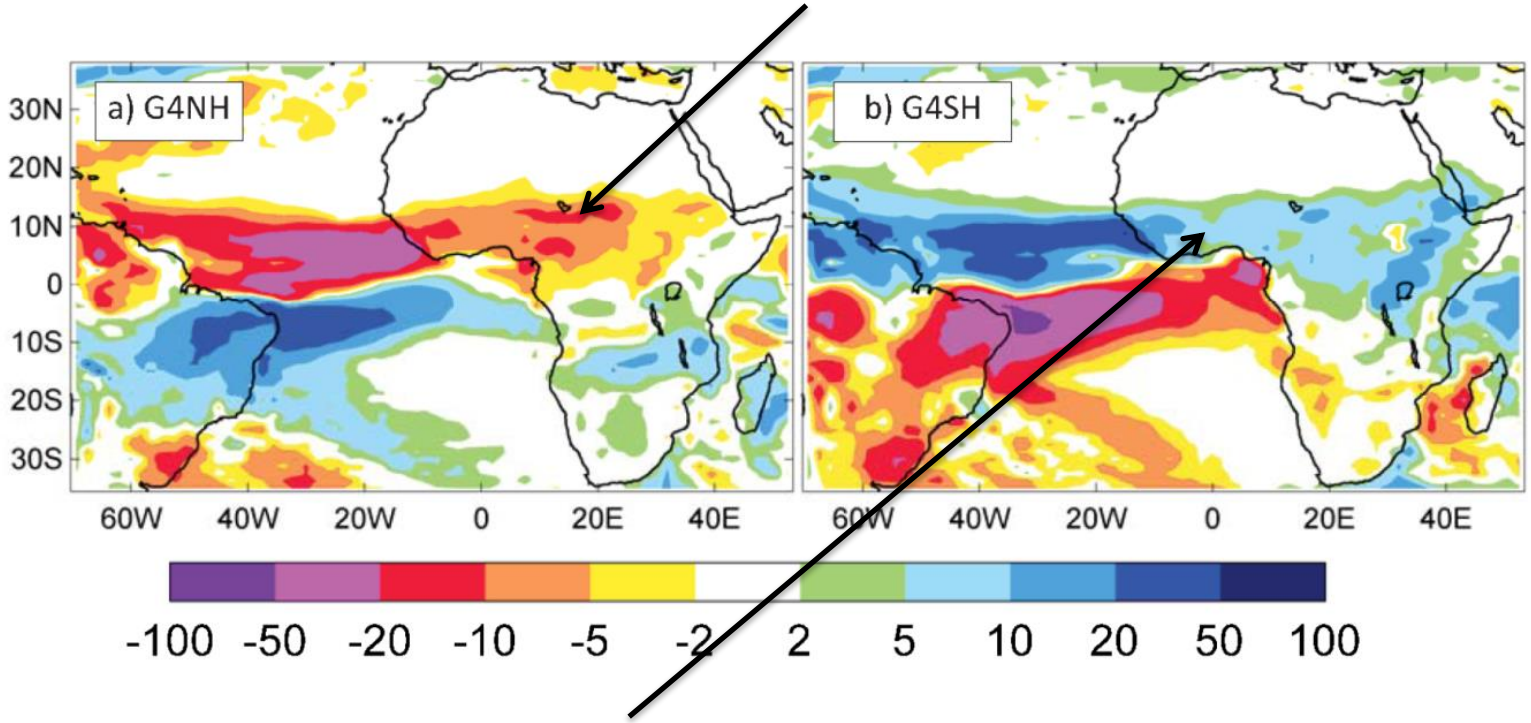
Even when we do, and the model behaviour in broad-scale dynamics is similar, there are specific inter-model differences that may be important (e.g. USA and Africa temperature differences between HadGEM2-ES and WACMM).



A word on single model studies

Dangers of Unilateral Stratospheric Geoengineering

Releasing sulphur dioxide only into the northern hemisphere stratosphere causes a severe drought across the Sahel.



Releasing sulphur dioxide into the southern hemisphere causes a significant greening of the Sahel.

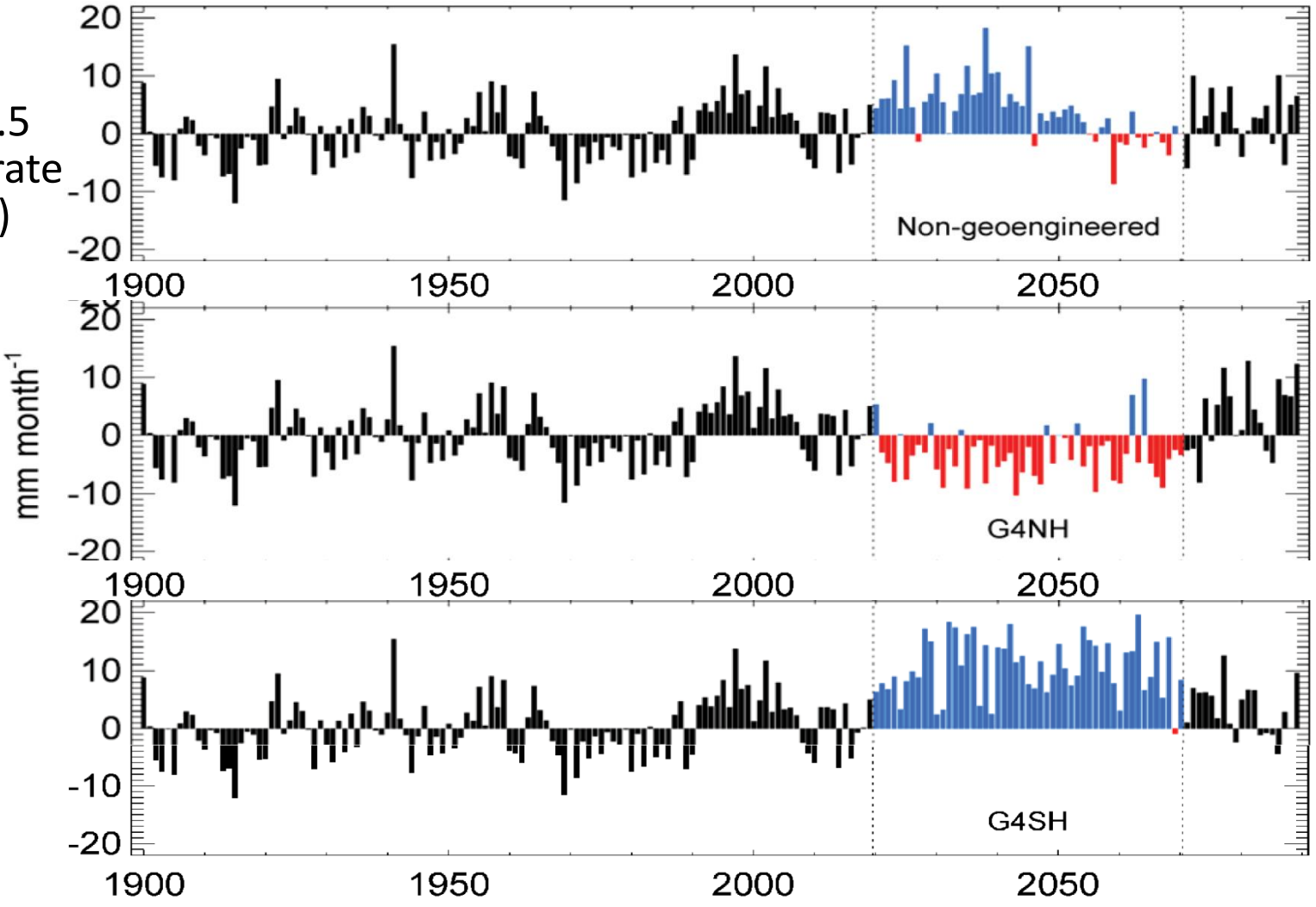
Haywood et al (2013) significant shift in African monsoon rainfall associated with geoengineeering

Sahelian precipitation anomalies

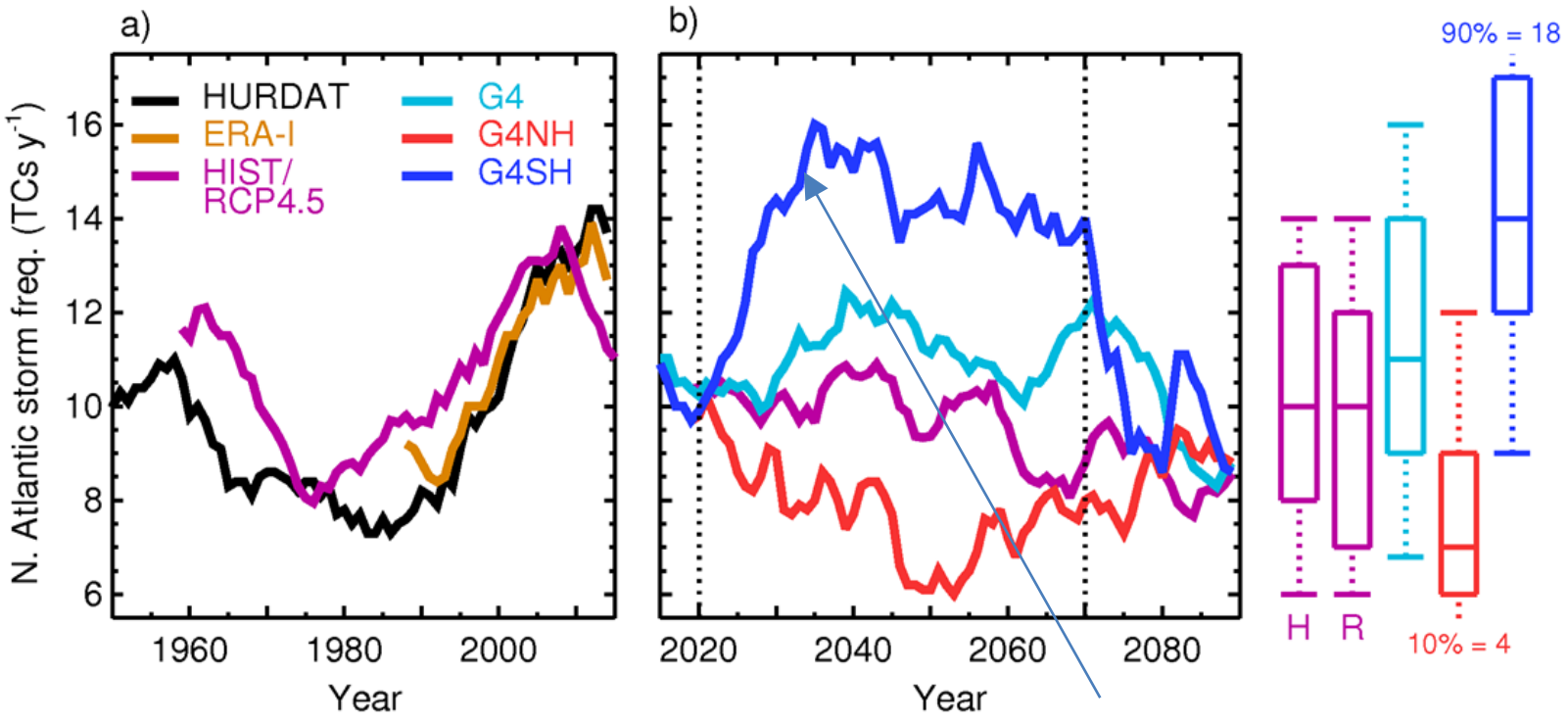
RCP4.5 (moderate CDR)

G4NH

G4SH



So could humanity inject into the NH to alleviate Sahel drought?



There is observational evidence to support these findings following the eruption of NovaErupta (Katmai, June 1912):

1913: Minimum in Nile and Niger river flow
1914: Only year without a single North Atlantic Hurricane

Injecting into the southern hemisphere will increase north Atlantic hurricane frequency by ~30%

Jones et al., Impacts of hemispheric solar geoengineering on tropical cyclone frequency, *Nature Communications, 2017*.

A word on natural analogues

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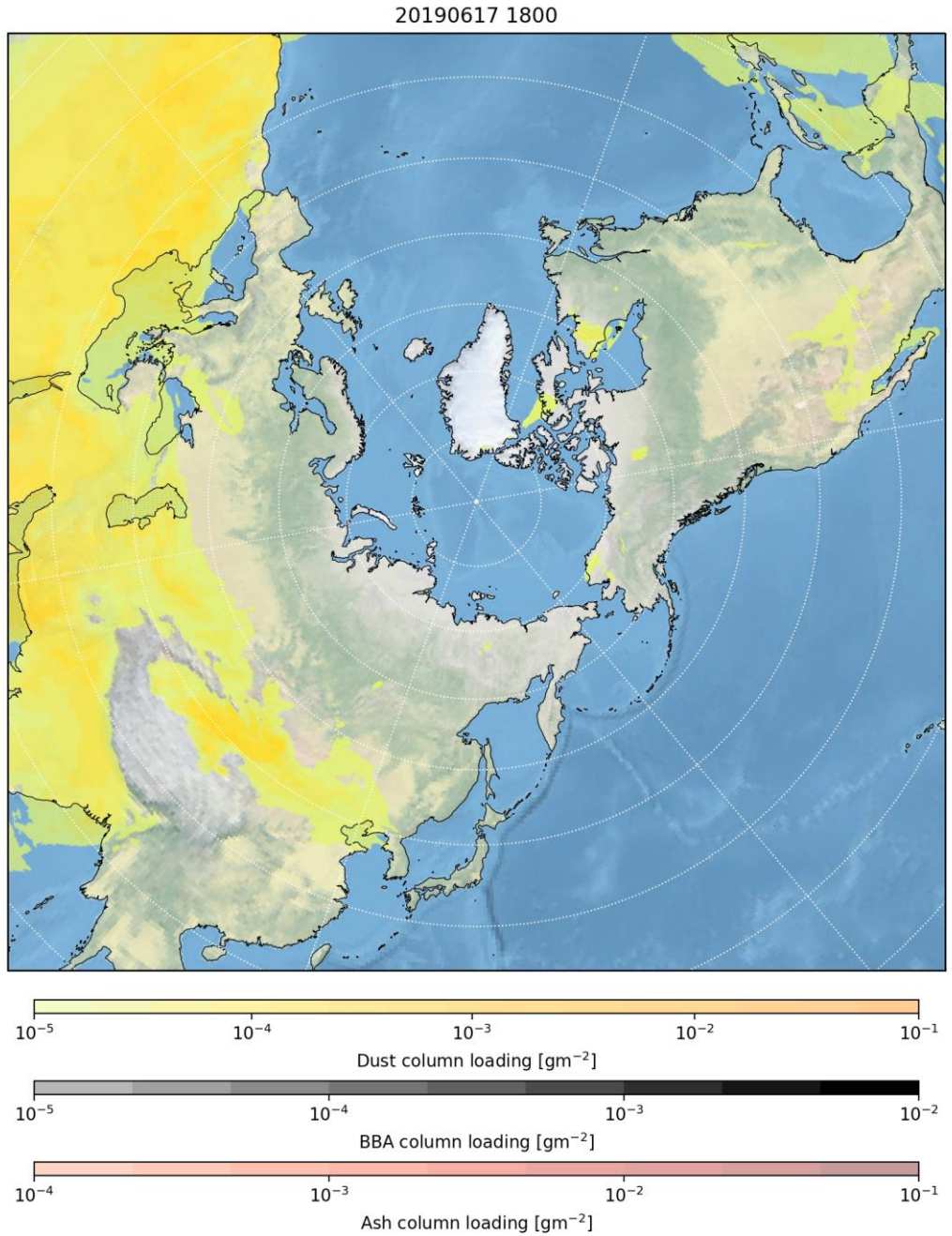
There have been many, many advances in both modelling & observations since Pinatubo 1991

There have been a number of significant stratospheric aerosol injection events in the last dozen years:

Kasatochi (July 2008, 1.5Mt SO2, high northern latitudes)
Sarychev (June 2009, 1.5Mt SO2, high northern latitudes)
Nabro (June 2011, 1.2Mt SO2, tropics, northern hemisphere)
Raikoke (June 2019, ~1.5Mt SO2, high northern latuitudes)

These allow us to test our models of stratospheric chemistry and transport



Raikoke in 2019

Simulations (Met Office NAME and NWP model) include:

Mineral dust (operational NWP model)

Biomass burning aerosol (pyrocumulus)

Ash/Sulphate

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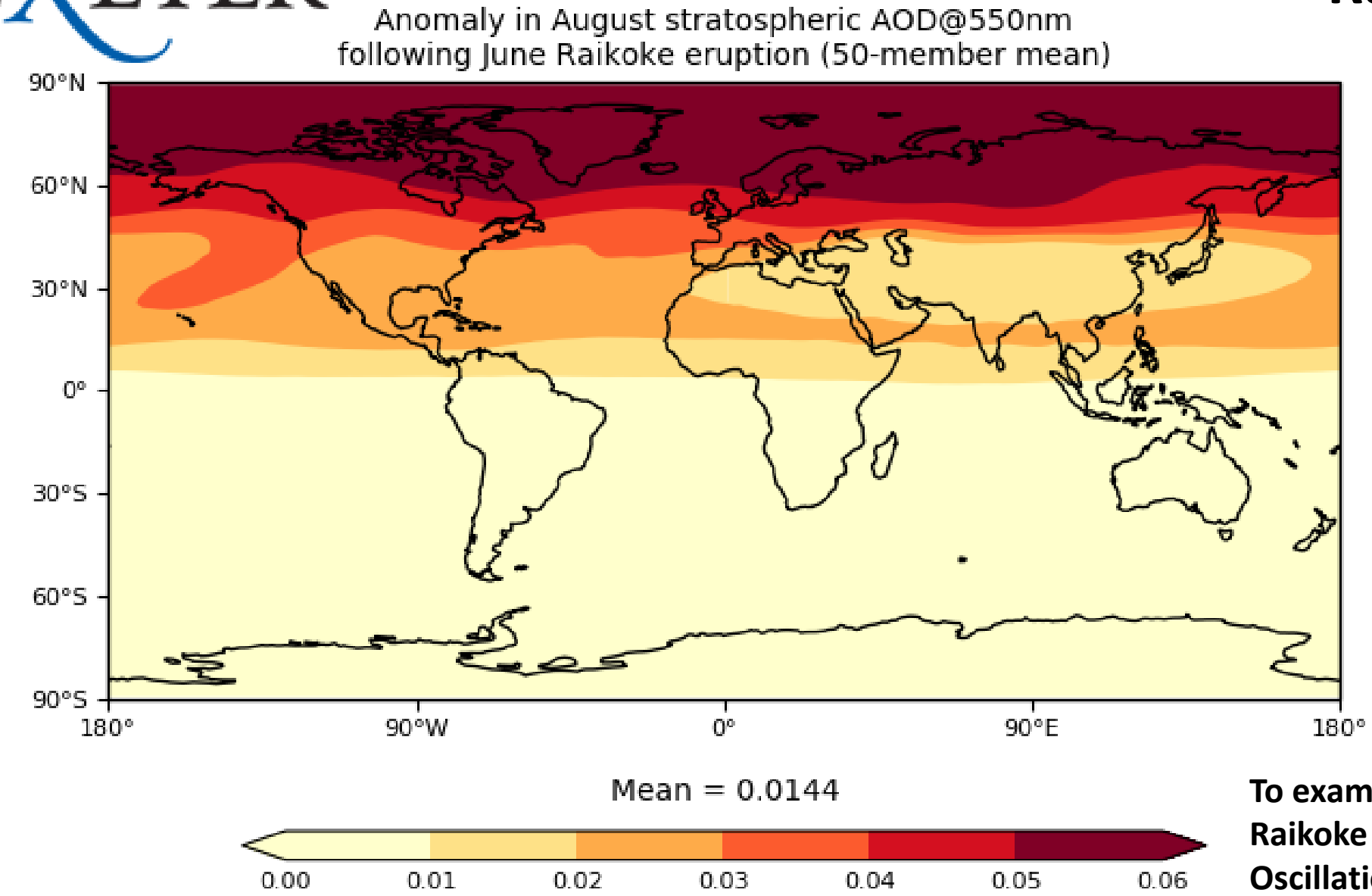
Raikoke in 2019



To examine the potential impact of Raikoke on the North Atlantic Oscillation & Seasonal Predictability

Conclusions:

- GeoMIP has proved invaluable for inter-model comparisons
- GeoMIP is moving to more policy-relevant scenarios using more comprehensive models.
- Single model simulations have shown the perils of unilateral geoengineering. Just don’t do it!
- SAI using SO2 is relatively advanced in terms of our understanding and is considerably enhanced by explosive volcanic eruptions. To move to other injection materials e.g. TiO2 etc would (in my opinion) be a mistake.
- Our knowledge gaps have closed considerably. They are now focussed very much on more regional aspects/extreme event reduction. This allows a more quantitative approach regarding humanitarian and economic losses against global warming scenarios.
- A geoengineered world may be imperfect, but may be less imperfect than that tainted by 150 years of industrial revolution.